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Online Voltage Instability Detection of Distribution Systems for Smart-Grid Applications

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(Abstract) This paper presents a developed voltage stability index for identifying the most sensitive buses to the voltage collapse in radial distribution networks. The developed index is based on the transferred active and reactive power of a distribution line. The developed index utilizes the continuous power-flow solution calculated using real time power-flow software in distribution management systems. The developed stability index is tested and validated using commercial continuation load-flow program. Then, the index is used to detect the voltage instability in real-time scenarios using a typical 24-hour daily load curves data of various demands with a 33-node radial feeder. The impact of distributed generation is also studied with varied daily environmental conditions including wind speed. The results show that the developed stability index provides fast assessment of the voltage instability in real time. The developed method fits with smart grid applications since the stability index can be easily integrated with the continuous power-flow solver utilized in distribution management systems.

Keywords: Voltage Stability; Stability Index; Distribution Systems; Wind Energy; Smart-Grid.

1. INTRODUCTION

Voltage instability is an important factor which should be considered in power system planning and operation since voltage instability would lead to system collapse. Voltage collapse typically occurs on power systems which are heavily loaded, faulted and/or has reactive power shortages. Voltage collapse is a system instability in that it involves many power system components and their variables at once. The voltage instability would lead to power system voltage collapse which may cause a failure of components or complete network blackout. Transmission and distribution systems become congested due to continuous increase of electricity demand and economical and environmental constraints to upgrade and expand existing systems.

Smart-grid aims to modernize the operation and components of existing systems. The basic building blocks of a smart-grid include assets, sensors used to monitor those assets, the control logic that realizes the desired operational status and finally communication among those blocks. Distribution management systems (DMS) are considered the control logic for operation and control of the smart-grid. DMS is usually equipped with a set of mathematical models that has ability to analyze the gathered data from distribution systems and find best conditions for secure and economical grid operation. DMS may involve the following main functions:

- Acquisition, processing monitoring and recording of Master Station (MS) and Remote End (RE) data (Digital Information and analog measurement of the electrical network).
- Detecting faults of Medium Voltage cables at kiosks (Distribution Transformer Points).
- Tele–control for Circuit Breakers at S/Ss or DPs and Load Break Switches at Kiosks.
- Power Application studies as Load flow, Short circuit calculations, etc.
- Integration with Geographical Information System (GIS).

Classical tools used to study the voltage instability problem such continuation load-flow analysis are well established and widely used for system design and planning. However, these tools may not be suitable for real-time voltage instability detection. The mathematical algorithms and models adopted for real-time operation should be reliable, efficient, and very fast. Jasmon and Lee [1] derived a voltage stability index for a stressed power station from a reduced system model. The index could identify how far a system is from its point of collapse. But it has two disadvantages. One is a big error and other one is the node voltages are not considered in the index expression. The bus stability indicator proposed by Chebbo [2], is obtained from calculating the magnitude of the ratio of Thevenin equivalent impedance to the load impedance at a given bus. Thevenin impedance at the jth bus is the jth diagonal element of the bus impedance matrix constructed after replacing all real/reactive loads by their equivalent impedances. The critical stability limit is reached when any bus indicator reaches to the value of one. A voltage stability index with respect to a load bus is formulated from the voltage equation derived from a two bus network and it is computed using Thevenin equivalent circuit of the power system referred to a load bus [3]. Eminoglu and Hocaoglu presented a voltage stability index for identifying the most sensitive bus to the voltage collapse in the radial distribution networks. The developed index is based on the transferred active and reactive power of the distribution line [4]. One such indicator is derived in [5] by using the minimum singular value of the

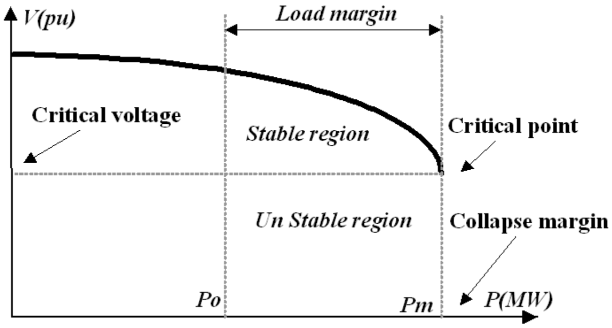


Figure 1. PV curve of a load bus in the power system.

power flow Jacobian matrix. A stability index is developed by Kessel et al. using bus admittance matrix of the system, line transferred power and bus voltages [6].

However, it is known that, developed indices of [5-6] are generally used for transmission systems and require calculation of the Jacobian [5] and bus admittance matrix [6] which may be singular or not readily available for particularly radial distribution systems. In addition, the index proposed in [2] requires calculation of the bus impedance matrix which may not be obtained for radial networks due to the singularity of the bus admittance matrix. Moghavvemi and Faruque [7-8] proposed bus/line stability indices which is obtained from the solution of the line receiving end reactive power equation [7] and the line receiving end active power equation of the reduced two-bus equivalent network [8].

Chakravorty and Das [9] proposed a new stability index based on well-known bi-quadratic equation relating the voltage magnitudes at the sending and receiving ends and power at the receiving end of the branch. The critical point is reached when the discriminate of the bi-quadratic equation related to any line is zero. In this case, the node with the minimum stability index is the most sensitive to the voltage collapse. Also in [10] a voltage stability index based on bi-quadratic equation relating the voltage magnitude at sending and receiving ends and power at the receiving end of the branch.

In this paper, an improved normalized voltage stability indicator is used in real-time operation to monitor the voltage instability of distribution power systems. The voltage stability index determines how the system is far from the voltage instability margin. The developed voltage stability index utilizes the continuous load-flow solution computed using smart-grid load-flow method [11]. The effect of the distributed energy penetration is taken into effect by inserting a wind turbine at the weakest bus and the presented results show the system performance enhancement with DG penetration. The results of the system stability using the proposed method are compared with the commercial software and show an exact agreement with it to determine the weakest bus in the system.

2. VOLTAGE STABILITY ASSESSMENT

Power system stability is defined as characteristic for a power system to remain in a state of equilibrium at normal operating conditions and to restore an acceptable state of equilibrium after disturbance; power system is voltage stable if voltage after a disturbance is close to voltage at normal operating condition. A power system becomes unstable when voltages uncontrollably decrease due to outage equipment (generator, line, transformer, bus bar, etc.), load increment, decrement of production and/or weakening of voltage control. The main factor, which causes these unacceptable voltage profiles, is the inability of the distribution system to meet the demand for reactive power. Under normal operating conditions, the bus voltage magnitude (V) increases as Q injected at the same bus is increased.

However, when V of any one of the system's buses decreases with the increase in Q for that same bus, the system experiences a state of voltage instability when there is a progressive or uncontrollable drop in voltage magnitude after a disturbance, increase in load demand or change in operating condition. According to [12] the definition of voltage instability is "Voltage instability stems from attempt of load dynamics to restore power consumption beyond the capability of combined transmission and generation system." The PV and QV curves are the most used to determine the loading margin of a power system at an individual load bus.

A typical PV curve of a load bus in a power system is shown in Figure 1. To build the PV curve, at a base case, the power system load is gradually increased. For each incremental load, it is necessary to recalculate power flows so that the bus voltage corresponding to the load is determined. The increment of load is stopped when the voltage collapse point or the nose of the PV curve is reached. The power margin between the current operating point and the voltage collapse operating point is used as a voltage stability criterion. In Figure 1, Po is the load power at the current operating point, and Pm is the maximum active power that the load can consume from the system.

3. DISTRIBUTION POWER-FLOW ANALYSIS WITH DG PENETRATION

The forward/backward sweep analysis solution process is described in Figure 2. The method have been developed such that be independent on DG models which have been developed in a separate routine.

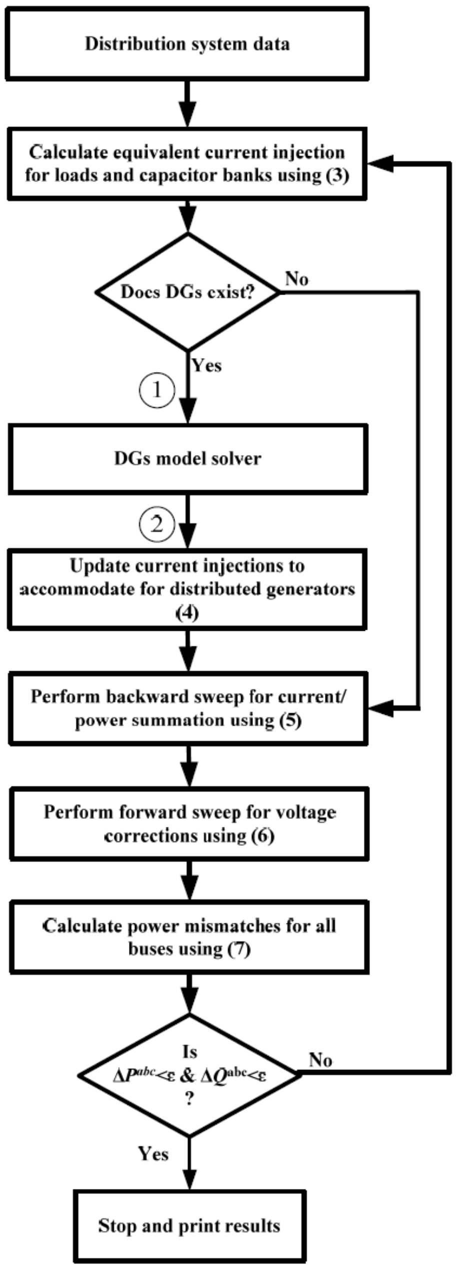


Figure 2. Radial power-flow solution considering distributed generation.

The circles given between points '1' and '2' represents the distributed generation solver. Regardless DG modeling details, DGs are represented by an equivalent current injection in the load flow solution process. The iterative solution continues till preset power mismatch is achieved.

4. DISTRIBUTED GENERATION MODELS

Distributed Generation (DG) has the potential to provide technical and economic benefits to the distribution system, such as the reduction of power losses and power quality improvement. On the other hand, it should be noted that, whether the DG is misused or misplaced, it may easily cause degradation of power quality, reliability, and control of the system or it may increase losses and affect voltage regulation. Distributed generation (DG) power can be directly injected to the grid or through converter interface circuit. For converter based distributed generation, the voltage source converter (VSC) controllers regulates the DC-link voltage, and thus there will be no interaction between steady-state model of the distributed generation unit and the distribution system. Hence, the converter based distributed generation can be directly represented by a negative PQ load at the PCC.

For three-phase grid directly connected such as synchronous or squirrel cage induction generators, complete steady state three-phase machine model should be embedded with sufficient modeling details into the power-flow program. Synchronous generators modeled as PQ or voltage controlled PV buses have been extensively reported in the literature. In this paper, sequential iterative process between the direct connected generator and the load-flow solution process as shown in Figure. 2

5. NORMALIZED STABILITY INDEX

There are many derivation are used for evaluating the stability index expression in distribution systems. In [7-8], the authors proposed bus/line stability indices which is obtained from the solution of the line receiving end reactive power equation and the line receiving end active power equation of the reduced two-bus equivalent network. Consequence, improvements lead to a stability index based on well-known bi-quadratic equation relating the voltage magnitudes at the sending and receiving ends and power at the receiving end of the branch [9-10]. The critical point is reached when the discriminate of the bi-quadratic equation related to any line is zero.

The developed index for real time voltage stability calculations [12-14] is based a two-node, say 'i', and 'j' line segment, the current flows in the line segment [3, 15]. The visible solution of the terminal voltage at node j is obtained by applying this condition:

$$\boldsymbol{b}^2 - 4\boldsymbol{ac} \ge 0 \quad (1)$$

$$\left[2\left(\boldsymbol{P_j R} + \boldsymbol{Q_j X}\right) - \boldsymbol{V_i}^2\right]^2 - 4\left[\left(\boldsymbol{P_j}^2 + \boldsymbol{Q_j}^2\right)\left(\boldsymbol{R}^2 + \boldsymbol{X}^2\right)\right] \ge 0 \quad (2)$$

The stability index normalization has been traditionally made using some division and multiplication manipulation of **Eq.2**. In this paper, the algebraic normalization of the index is made simply by adding one to the terminals of **Eq.2** as follows:

$$1-[2(\boldsymbol{P_j R}+\boldsymbol{Q_j X})-\boldsymbol{V_i}^2]^2+4[(\mathrm{P_j^2}+\mathrm{Q_j^2})(\mathrm{R}^2+\mathrm{X}^2)]\le 1 \quad (3)$$

The new normalized voltage stability index at bus 'j' is defined by:

$$\boldsymbol{L_j} = 1-[2(\boldsymbol{P_j R}+\boldsymbol{Q_j X})-\boldsymbol{V_i}^2]^2+4[(\mathrm{P_j^2}+\mathrm{Q_j^2})(\mathrm{R}^2+\mathrm{X}^2)] \quad (4)$$

Where L_j stands for the voltage stability index of bus j, the voltage stability index of total distribution system is defined by:

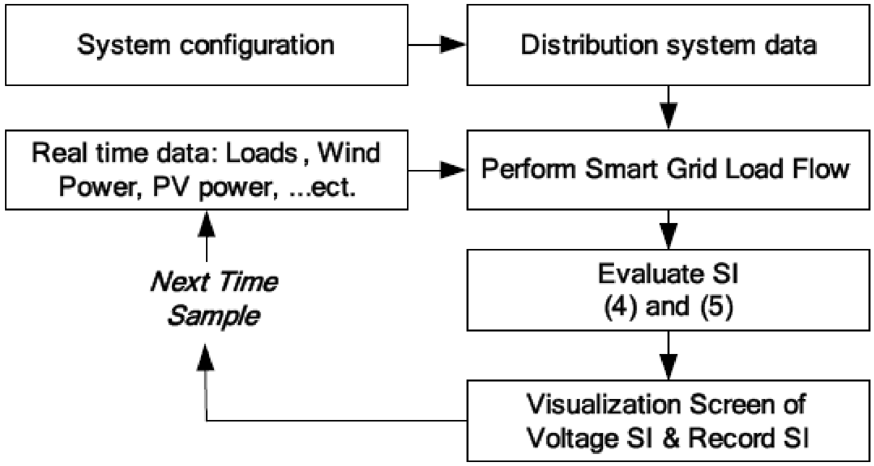


Figure 3. Real time instability detection in distribution management systems.

$$\boldsymbol{L} = \max[\boldsymbol{L}_1, \boldsymbol{L}_2, \boldsymbol{L}_3, ...\boldsymbol{L}_N] \quad (5)$$

The branch corresponding to the index value *L* is called the weakest branch. The voltage collapse must start from the weakest branch. Therefore, the margin of voltage stability can be obtained according to the deviation between *L* and the critical value 1.0.

6. REAL-TIME VOLTAGE INSTABILITY DETECTION ALGORITHM

Figure 3 shows the real-time implementation of the proposed normalized voltage stability index. The developed stability index expression requires the steady state voltages and active and reactive line-flows which are obtained from the continuous power-flow solution available in distribution management systems (DMS). Smart grid load-flow analysis in distribution systems are usually solved using the radial power-flow program which can handle a variety of system models and fits well with continuous power-flow solution requirements [11]. The real-time data are gathered from the network through the DMS infrastructure. As the load-flow is performed, the active and reactive line flows are computed for the stability index evaluation. The stability index and its maximum value are visualized for different nodes against time. The visualized data of the SI enables the operator engineer in DMS to monitor the weakest parts of the distribution systems with the continuous load variation in real time.

7. RESULTS AND DISCUSSIONS

The 33 node radial feeder is used in this paper to demonstrate the application of the real time voltage stability assessment of distribution systems. The full system data of the feeder is given in [16]. The real time scenarios are modeled using typical daily load curves for various load types. The normalized daily load data is available in [17]. The following case studies are tested and discussed:

Case 1: base case load flow for SI validation against commercial continuation load-flow tool

Case 2: 24-hour daily load analysis for real time simulation with wind energy systems

7.1. Case 1: Stability Index Expression Verification

The validation of the developed stability index expression is performed by comparing the calculated stability index with the PV curve calculated using NEPLAN commercial voltage stability software. **Figure 4** shows the PV curves of the system buses against the load factor λ. **Figure 4** demonstrate that bus 18 has the minimum voltage value with increasing load factor. This indicates that bus 18 is the most sensitive bus to voltage collapse in the system. **Figure 5** shows that the maximum values of stability indices for all system buses and shows that bus 18 has the maximum stability index. This confirms that it is the most sensitive bus to instability. From **Figure 4** and **Figure 5,** it can be found that the developed voltage stability index can directly determine the weakest bus in the network. **Figure 6** shows a comparison between the calculated stability index and the PV curve of the weakest node in the study system. The result shows that the normalized stability index reaches to its maximum value, i.e. '1.0', when the voltage reaches the nose of the curve. The figure exhibits the accurate normalized curve expression.

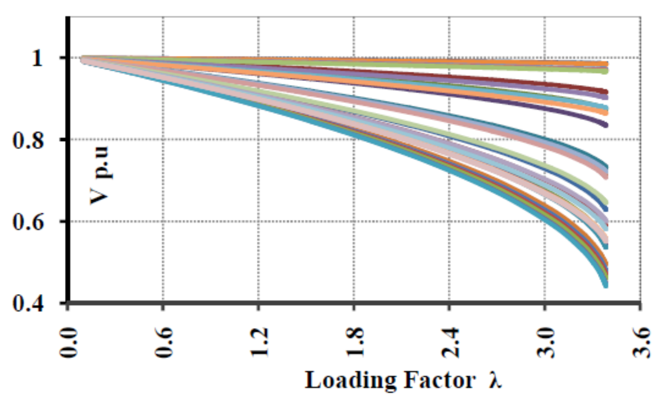


Figure 4. PV curves for 33 bus system.

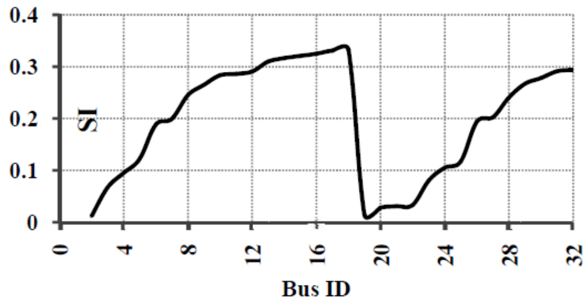


Figure 5. Normalized voltage stability index for 33 bus system at base case.

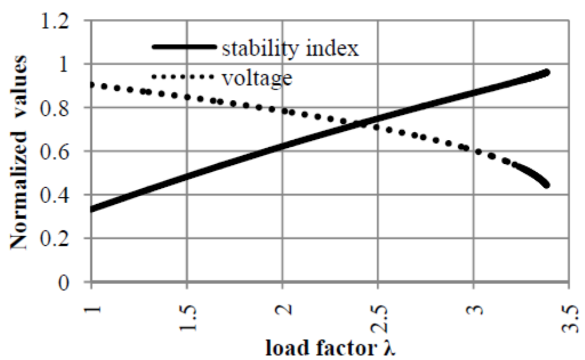
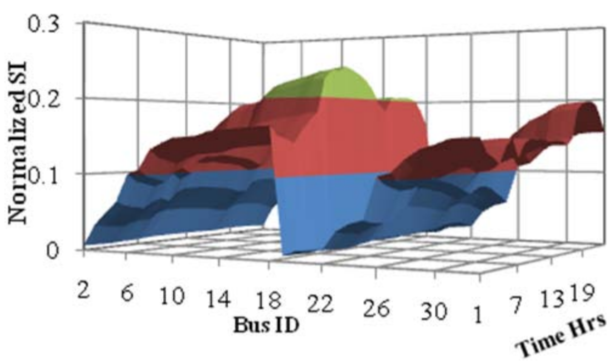
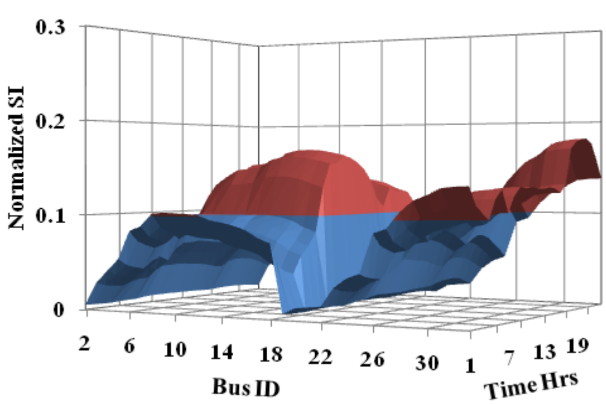


Figure 6. Comparison of the SI with the corresponding voltage calculated using continuation power-flow program.



(a) without DG



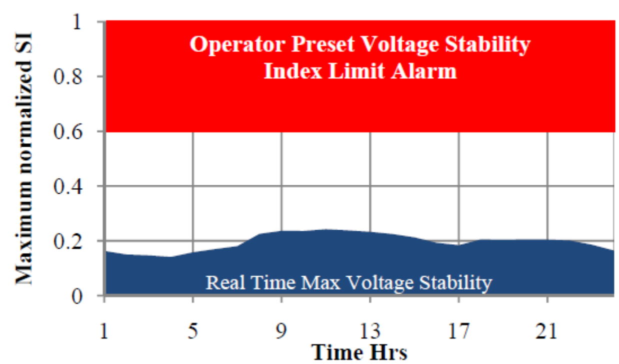
(b) with wind turbine generator connected at bus 18

Figure 7. Normalized stability index with load daily demand variation.

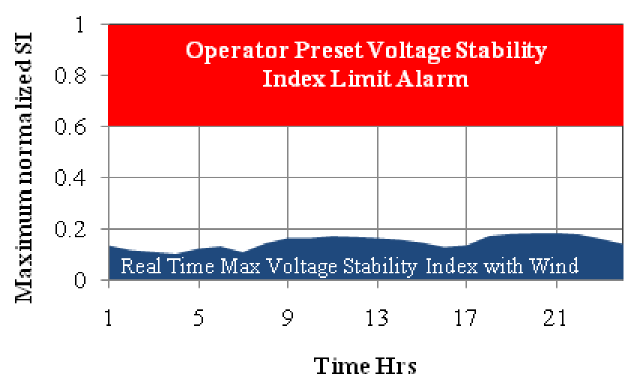
7.2. Case 2: 24-Hour Voltage Stability Index Monitoring

In real time, the demand is changing according to consumers' needs. Typical daily load curves of different demands are considered here. These loads include residential loads, small industrial loads, lighting loads…etc. A 24-hour period is simulated using the developed method. The system is firstly simulated without any distributed energy penetration as shown in **Figure 7a**. Then the system is simulated with a wind turbine connected at node 18 as shown in **Figure 7b**. The maximum normalized stability indices for the both cases are shown in **Figure 8a** and **Figure 8b**, respectively, for the 24-hr period. It can be concluded from Figure 8 that with DG penetration the stability indices are reduced meaning that the system stability is improved.

The results consider the impact of wind speed variation on the generated power for the wind turbine generating system. The injected power at node 18 due to the wind energy system enhances the system voltages stability as exhibited in **Figure 8b**. Since the interest is usually directed to the weakest buses, the maximum stability index is plotted with the simulation time. The above, 'red', dark parts exhibits the preset alarm for instability detection of the system.



(a) without DG



(b) with wind turbine generator connected at bus 18

Figure 8. Normalized maximum stability index with load daily demand variation.

On the other, the lower dark curve, 'blue', shows the variation of the maximum stability index with demand

variation. The area between the upper limit and the lower curve shows the margin which indicates for the operator how much the system is far from the preset instability alarm in the distribution management system. The proposed technique in this paper utilizes the continuous power-flow algorithm which is used to simulate smart grid in real time. The developed model provides a very fast and robust tool to assess the stability of distribution systems and allow operator engineers to consider corrective actions before the system become at risk or the problem is transferred to the transmission grid due to the operation of control devices.

8. CONCLUSIONS

This paper provides online voltage stability tool for distribution power systems. The method is based on an improved normalized stability index and utilizes the continuous power-flow solution calculated using smart grid load-flow program. The method is simple as well as accurate to implement in distribution management systems. In this method, no need for specific hardware infrastructure for synchrophasors utilized in transmission grid. The developed method includes the investigation of the of distributed energy impact in real time. The results of the system stability using the proposed method are compared with the commercial software and show an exact agreement with it to determine the weakest bus in the system.

9. ACKNOWLEDGEMENTS

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